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Predictive Modelling of Fisheries Habitat Loss and Replacement

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Author(s): R. Lanno and C. Wren - Ecological Services for Planning Ltd.

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Contact Person: Jack J. Armstrong, Materials Office, Research and Development Branch, MTO
(416) 235- 5254

Abstract: In response to a Request for Proposals from the Ontario Ministry of Transportation, we reviewed various models relating fish production or fish biomass to environmental variables in fluvial habitats to determine their potential for use in habitat compensation issues. The four major models found in the literature were the Habitat Quality Index (HQI), the Ontario Trout Habitat Classification Model (OTHC), the Habitat Suitability Index (HSI), and the Instream Flow Incremental Methodology (IFIM). A similar review of models (Fausch *et al.* 1988) was also assessed. Models were either too general and lacked the precision necessary to predict fish biomass, or could predict fish biomass in a given stream and lacked generality for application to other streams. No single model could be applied to a given reach of stream and accurately predict fish biomass from environmental variables without additional model validation and testing. Methods to improve models include:

1) Use *a priori* classification of streams to enhance model precision;

2) Standardize measurement of model variables;

3) Develop a rule-based expert system for determining habitat suitability; or

4) Adopt the HSI methodology to evaluate habitat suitability and not consider habitat utilization.

Comments:

Key Words: fish, habitat, biomass, models, review, production, Habitat Suitability Index (HSI), Habitat Quality Index (HQI), Instream Flow Incremental Methodology (IFIM), Ontario Trout Habitat Classification (OTHC)

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R. Lanno

C. Wren

Ecological Services for Planning Ltd.

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For additional copies, contact:
The Editor, Technical Publications
Room 320, Central Building
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8

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1/ Introduction

The Fish Habitat Management Section of the Department of Fisheries and Oceans (DFO) and the Ontario Ministry of Natural Resources (MNR) have recently applied more stringent requirements under Section 35 of the Federal *Fisheries Act* for the prediction and mitigation of impacts on fisheries caused by highway works in and adjacent to potential fish habitat. The agencies stress that the objective of the policy framework for fish habitat management is a net gain of productive capacity for fisheries resources through fish habitat conservation, restoration and development. As a result, the Ontario Ministry of Transportation (MTO) is required to meet two principal requirements in order to obtain approval for works under this Act:

1) Predict the impact on fish or fish habitat, including the loss or gain, that will result from the proposed works; and,
2) Identify the design measures that will effect the replacement, and possibly the increase, of the habitat lost and achieve the objectives of the *Fisheries Act*.

The objectives of this report are two-fold:

1) To identify and evaluate available models, rule-based expert systems, or habitat evaluation approaches that relate key biological parameters to fish production or biomass in lotic environments. The models should be able to assess fish production or biomass of the affected habitat (eg. at, downstream, or upstream of a culvert crossing; channelized or filled reaches of a stream), as well as that of habitat restored by compensation measures, permitting MTO to meet the requirements of the *Fisheries Act*.
2) Identify parameters in the models, rule-based expert systems, or habitat evaluation approaches that can be varied by the planner/designer during the project development stage. Variation in horizontal and vertical configuration and flow pattern of the watercourse, instream structures, and riparian measures may ensure that the productivity of the watercourse is maximized for the natural fish species present before work.

Fisheries managers face an ongoing problem of placing a value on fishery resources, especially in conjunction with cost-benefit analysis for water resources development projects. It is often difficult to decide which variables are indicative of the value of the

habitat and what their relative value is in terms of compensation. Maximizing fish production or biomass for target species within a given reach of stream would satisfy objectives of the *Fisheries Act*.

It is often expensive and time consuming to directly measure fish production or biomass even in a small percentage of fluvial habitats that may be affected by construction works. Monitoring such factors as daily variation in water temperature or quantifying intricate physical factors such as cover may also be impractical and subjective. A more realistic approach would be to develop simple relationships to predict fish production or biomass (standing crop) in a given reach of fluvial habitat based upon easily measured physical and chemical factors or to develop procedures that would allow the on-site quantification of suitable fish habitat.

There exist a number of models that relate production, biomass, or standing crop of fish in lotic systems to environmental variables. Many of these models were developed since 1970, although fisheries biologists have attempted to link environmental variables to fish production for a number of years (Allen 1951; McKernan 1950). The models available to predict standing crop of stream fish from habitat variables, up to and including August 1985, were reviewed in detail by Fausch *et al.* (1988). The results of our literature review will be compared with those of Fausch *et al.* (1988) in the last section of this report. The objective of this report is to review in detail the most common or widely used models and assess their potential for application in southern Ontario.

2/ Methods

2.1/ Literature Search

Computerized literature searches of on-line databases including AQUAREF, NTIS, and AQUATIC SCIENCES AND FISHERIES ABSTRACTS, were conducted to ensure that documents from the primary literature as well as those from government agencies were found. The major keywords that were used to search various databases were combinations of FISH and PRODUCTION and STREAM or RIVER. The databases searched and the number of hits on the search keywords are presented in Table 1. Literature searches of the holdings at the libraries of the University of Guelph and the University of Waterloo were also conducted.

Table 1/ Summary of databases searched and the number of hits in each database.

Database	Number of hits
AQUAREF	40
NTIS (National Technical Information Service)	20
AQUATIC SCIENCES AND FISHERIES ABSTRACTS	155
WATER RESOURCES ABSTRACTS	44
WAT-TOX	20

Pertinent documents from agencies including the MNR, DFO, Federal Highway Administration, U.S. Fish and Wildlife Service, and the U.S. Department of Transport were reviewed. The Citation Abstracts and library holdings were also searched for the most recent relevant publications by prominent authors in the field of fish biomass modelling. In addition, prominent scientists conducting research on fish habitat modelling were contacted. Results of the literature and library searches revealed that relatively few models were published in primary journal articles. Many models cited in government publications were difficult to obtain. Conversation with Jack Imhof and Jim Bowlby,

specialists in fish habitat utilization with the MNR, confirmed that the models discussed in this document would cover all the widely recognized and utilized models relating fish production or biomass to environmental variables.

2.2/ Definition of Terms

A **model** is a physical, mathematical, or conceptual representation of a real entity. **Mathematical models** are expressions of relationships between defined entities expressed in quantitative terms and can be categorized as mechanistic, empirical, or descriptive. **Mechanistic** models are predictive and attempt to explicitly explain the mechanisms underlying dynamics of the system being modelled. **Empirical** models are also predictive but implicitly account for mechanisms underlying the dynamics of the system and do not require an understanding of cause-effect relationships. **Descriptive** models are not predictive but partition the variability within a system to determine what parameters contribute most to variability. Most of the mathematical models assessed in this review were descriptive or empirical in nature. Models can also be **conceptual** or **narrative** in nature such as rule-base expert systems, classification systems, and screening procedures.

Production in biological systems may be defined as the sum of all organic matter added to the stock of a product in a unit time (Ivlev 1945). Production estimates require data regarding fish abundance, growth rates, and the rate of change in numbers of fish. Since production is a single variable that accounts for the dynamic components of growth, mortality, recruitment, population density, and migration, it has often been considered one of the best criteria to assess the overall performance of a particular population (Le Cren 1969). **Standing crop** is the concentration of a population for a given area and may be expressed as the number of animals, weight, or energy content. **Biomass** is a common expression of standing crop and may be defined as the amount of tissue present in a given area of river (eg. kg/ha) and may be estimated by the density of fish x mean weight. Most of the models reviewed used standing crop or biomass, rather than production, as a dependent variable

The models that will be described in this document attempt to relate a wide range of variables to fish production. These variables may be classified as **biological**, **chemical**, **physical**, or **anthropogenic**. **Biological** variables are those that are direct or surrogate measures of biological entities in a stream. **Chemical** and **physical** variables deal directly with those attributes of a stream. **Anthropogenic** variables are measures that may be imposed upon fish production or biomass directly by humans. Examples of the different types of variables encountered in models are given in Table 2.

Table 2/ Variable types related by models to fish production or biomass

Variable Category	Example of variable
Biological	Presence of piscivores
	Benthic invertebrate biomass (g/m^2)
	Suspended ATP concentration (ng/L)
Chemical	Alkalinity, hardness
	Total phosphorus
	Nitrate, pH
Physical	Mean temperature
	Maximum temperature
	Late summer stream flow
	% pool area
	Substrate composition - % silt, sand, gravel
	% bank cover
	% eroding banks
Anthropogenic	Angling harvest
	Stocking of fish

3/ Review of Models

Two major models were found during the literature review: mathematical and rule-based expert system types. Although many models have been developed for predicting fish production or standing crop from different environmental variables (Fausch *et al.* 1988), the best known and most widely used mathematical models are summarized in Table 3.

Table 3/ Summary of common models predicting fish production or standing crop from environmental variables

Model	Model Type	Reference
Habitat Quality Index (HQI)	Regression (Simple and multiple)	Binns and Eiserman 1979
Ontario Trout Habitat Classification (OTHC)	Multiple regression and discriminant analysis	Bowlby 1986
Habitat Suitability Index (HSI)	Compounded index	Raleigh 1982
Instream Flow Incremental Methodology (IFIM)	Hydrological flow and HSI	Bovee 1982, 1986

3.1/ Habitat Quality Index (HQI)

The Habit Quality Index (HQI) (Binns 1979; Binns and Eiserman 1979) is one of the most widely known and used models for relating the standing crop of trout in streams to biological, chemical, and physical environmental parameters. Each trout habitat variable at each site is rated with respect to its quality for trout on a scale from 0 (worst) to 4 (best) to remove nonlinear relationships that may exist between trout standing crop and habitat. The mathematical relationship between trout standing crop (g/m^2) and habitat variables is presented in Appendix A. Two of the major assumptions associated with this model are:

i) The best trout habitat would be associated with a high standing crop of trout

ii) Standing crop of trout is a consistent index of existing habitat quality

Habitat parameters used in this model considered the most important abiotic factors for fluvial fish habitats to be temperature, rate of water flow, fluctuation in discharge, and cover availability (Hynes 1979). Parameters related to these major variables were selected based upon availability from other sources (eg. flow-monitoring stations) and ease and accuracy of measurement. The selected parameters are presented in Table 4.

Table 4/ Environmental variables employed during HQI Model I Development. Parameters in bold were significantly correlated (α=0.05) with trout standing crop

Biological	Physical	Chemical
Stream bank vegetation	Turbidity	Total alkalinity
Fish food type	Stream depth	Total phosphorus
Fish food abundance	Stream morphology	Total dissolved solids
Fish food diversity	Bed Material	Hydrogen ion (pH)
	Silt deposition	**Nitrate nitrogen**
	Substrate	
	Late summer stream flow	
	Maximum summer stream temp	
	Annual stream flow variation	
	Cover	
	Eroding stream banks	
	Water velocity	
	Stream width	

The period of parameter estimation was standardized to August and the first half of September, when water flows in Rocky Mountain streams were lowest to facilitate sampling, and trout were theoretically most stressed. In order to satisfy model assumptions, potential HQI sites were screened to eliminate reaches that were heavily stocked or subject to severe perturbations, such as channelization. After data collection and field measurements were completed, habitat parameters were rated on a scale of 0 (worst) to 4 (best) according to the criteria presented in Binns and Eiserman (1979).

Binns and Eiserman (1979) developed two distinct models (Model I and II) that related environmental variables to trout biomass. For each model, multiple regression analysis of habitat variables on trout standing crop was conducted to determine relationships. In

Model I, eight variables were significantly ($\propto$=0.05) correlated with trout standing crop (Table 4), while four others (late summer stream flow, turbidity, maximum summer stream temperature, bank vegetation) were almost significant. Bank vegetation and turbidity did not enhance model performance and were dropped from the model. Model I explained 95% of the variation in standing crop of trout and had a high correlation coefficient (R = 0.977). In order to simplify the model, fish food abundance and diversity parameters were replaced with a substrate parameter in Model II. The P factor used in Model I (Appendix A) was replaced by shelter index and food index factors. Model II explained 97% of the variation in trout standing crop, exhibited an improved correlation (R = 0.983), and a decreased residual sums of squares in the ANOVA, suggesting an increase in model precision.

The HQI can predict changes in trout standing crop due to habitat improvement projects. However, anomalies in trout population density, such as those caused by extremes in climatic conditions, flow regulation, and angler harvest, may cause variability in HQI predictions. The HQI must also be used with caution in rivers containing established brook trout populations and many beaver ponds (Binns, pers. comm.).

Fausch *et al.* (1988) suggested that interpretation of this model is difficult due to its general form as a power function and the fact that it is fitted using multiple regression by transforming both dependent and independent variables to logarithms. The relative prediction error may be most significant in judging model accuracy due to one inflated data point. The relative prediction error for biomass at 16 new sites was 38% for Model I and reduced to 12.5% for Model II at 8 other new sites.

Whether the HQI is applicable to fish populations in geographical regions other than the Rocky Mountain streams of Wyoming where it was developed is equivocal. The HQI was closely related to standing crop of stream salmonids in Wyoming (Annear and Conder 1983), but other researchers found that the HQI consistently overestimated standing stocks of trout in Montana (White *et al.* 1983), and only explained 6.7-9.2.% of the variation in trout biomass in southern Ontario streams (Bowlby and Roff 1986).

Scarnecchia and Bergersen (1987) attempted to develop simple empirical relationships for predicting trout production in small, permanently flowing, Colorado streams on the basis of easily measured physical and chemical parameters (Table 5). This approach was quite similar to the HQI (Binns and Eisermann 1979) and actual testing of the HQI model was conducted on the test sites. The streams studied were all perennial, contained trout populations consisting of several age-groups, were small enough for reliable population estimates, and were either lightly fished or unfished. Relationships between production, biomass, physical and chemical factors, and HQIs were investigated using simple, multiple, and stepwise regression, and analysis of variance techniques. Trout production was related inversely to elevation and directly to substrate diversity, conductivity, hardness, and alkalinity. Of the five variables significantly related to production, all but one (substrate diversity), were autocorrelated. Midsummer biomass of trout in these creeks was significantly related to HQIs (Binns and Eisermann 1979) one year (1979), but not the next (1980). Combinations of various factors such as elevation and width:depth ratio; elevation and substrate diversity; elevation, substrate diversity, and percentage of zero-water-velocity stations; and elevation, width:depth ratio, and alkalinity, explained much of the variation in production and midsummer trout biomass. A strong correlation was also evident between midsummer biomass and annual production.

Table 5: Environmental variables employed by Scarnecchia and Bergersen (1987). Parameters in bold were significantly correlated (α=0.05) with production or mean trout biomass

Physical	Chemical
Elevation	**Alkalinity**
Substrate	**Hardness**
Width:depth ratio	**Conductivity**
Mean width	
% 0-velocity stations	
Mean velocity	
Discharge	
Undercut banks	

3.2/ Ontario Trout Habitat Classification Model (OTHC)

The Ontario Trout Habitat Classification (OTHC) model (Bowlby 1986) was developed to relate trout stream habitat variables to trout biomass in 30-m long sample sites of relatively constant habitat conditions (Appendix A). To account for the great variability in trout biomass density during the summer, stream habitat was classified into broad categories of trout biomass density using discriminant function analyses. The model classifies sites into the following trout biomass density (g/m^2) categories: 0-0.8 (poor), >0.8-2.7 (fair), >2.7-6.4 (good), and >6.4 (excellent). Bowlby *et al.* (1989) note that it may be necessary to include additional categories at the upper end of the classification as more data become available. The model included candidate variables for modelling trout habitat quality identified by Bowlby and Roff (1986) representing food, shelter, water quality, and living space. Rather than remove potential nonlinearities in data by using ratings or indices, as in HQI and IFIM models, the authors chose to use the data in raw form or square root or logarithmic transformations.

The model showed that trout biomass in southern Ontario is correlated with microcommunity biomass (measured as the ATP content of the suspended solids, representing bacteria, fungi, and algae), percent pool area, mean maximum summer temperature, biomass of small benthic invertebrates, presence of piscivorous fish, and a variable representing pools and overhead cover (Table 6). ATP concentration of the suspended solids appeared as the most important predictor of trout biomass density, and may be a surrogate variable for localized groundwater inflow which, in turn, is beneficial to the early life stages of trout. Bowlby and Roff (1986) also found that in the presence of piscivores, the biomass of non-piscivorous fish was lower and the biomass and abundance of benthic invertebrates were higher than in the absence of piscivores.

When tested in southern Ontario sites, the model correctly classified 8 of 13 sites. Four of the five incorrectly classified sites contained trout >30 cm in length and were placed in a lower trout biomass density category. The authors suggest that if piscivory significantly altered trout biomass and is responsible for the misclassification of these

sites, then the OTHC may adequately assess the relationship between trout and physical habitat variables in southern Ontario streams.

Table 6: Environmental variables employed by Bowlby (1986) in the development of the OTHC model. Variables in bold were significantly correlated (α=0.05) with mean trout biomass

Biological	Physical
Abundance and biomass of drift by 3 size classes	Maximum and minimum weekly summer temperature
Abundance and biomass of benthos by 4 size classes	**Mean maximum summer temperature**
Sediment microcommunity biomass (ATP)	Current velocity at thalweg
Suspended microcommunity biomass (ATP)	Width
Sediment organic matter	Depth profile
Suspended organic matter	**% pool area**
Presence of piscivores	% silt, sand, gravel, rubble, boulder, clay, bedrock
	% organic debris
	Substrate diversity
	% log cover, bank cover, brush cover
	% aquatic vegetation cover, rock cover
	Cover diversity

3.3/ Habitat Suitability Index (HSI) and Habitat Evaluation Procedures (HEP)

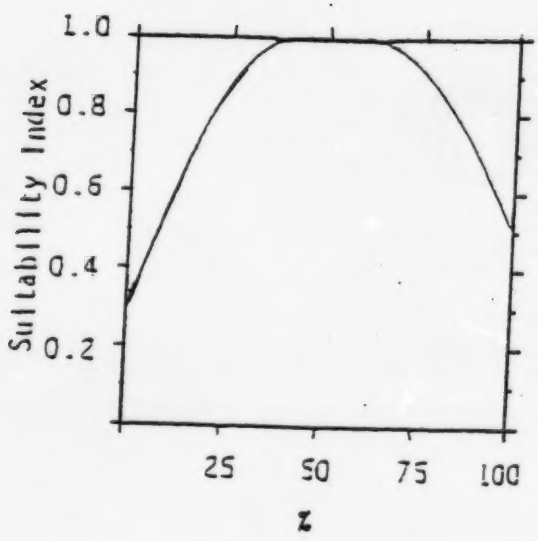
3.3.1/ Habitat Suitability Index (HSI)

The HSI model, in its present form, is intended to serve as a relative indicator of habitat suitability for a given species, not to predict standing crop from habitat variables. Both the IFIM and HEP techniques employ Suitability Index (SI) curves to compare a measured habitat variable with observed optima for a particular species and variable (Figure 1). The index values for any SI curve or HSI for any species or life stage can vary from 0.00 to 1.00 and indicates a range from unsuitable to optimum habitat, respectively. Each variable in the HSI model is assigned an index value from its respective SI curve and the product of the index values of all the variables in the model is calculated to give a final HSI index value (Appendix A). Depending upon the desired model, the HSI index value may be composed of different life stage components. In other words, an HSI index value may be calculated for a specific life stage component, if desired.

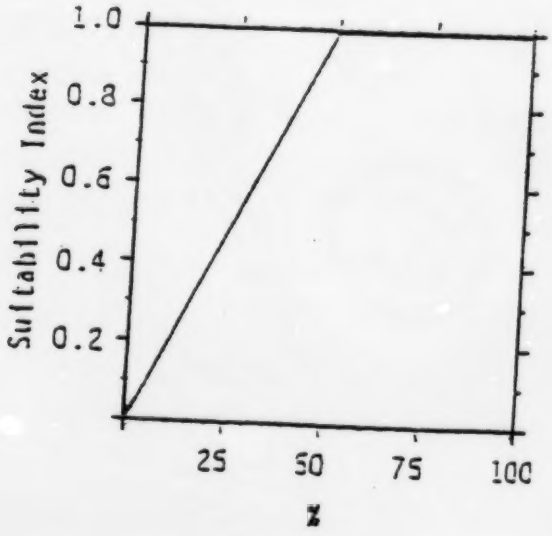
Comparisons of habitat potential are based on a single number representing habitat conditions throughout the year, and consequently can be a relatively static appraisal of this characteristic (Appendix A). The HSI index value is used to rate overall habitat quality in applications of the HEPs. When multiplied by the corresponding evaluation area, the HSI yields the total HUs for the species being considered. HUs then become the standard of comparison for evaluating habitat gains or losses due to natural or anthropogenic changes in the environment. Three primary assumptions are implicit in the validation of HSI with standing stock of fish:

1) populations are measured accurately and are at carrying capacity when the evaluation is conducted;
2) habitat quality is measured accurately and is limited primarily by the physical variables included in models;
3) field sampling sites provide representative subsamples of species habitat and self-sustaining fish populations.

A major criticism of the HSI models is that each model requires the measurement of too many variables (eg. Table 7), all of which are believed to be significant in determining the fish biomass a lotic system can support. The models discussed previously in this report suggest that it may not be necessary to measure all of these variables to determine carrying capacity or biomass. Models should be streamlined by determining which variables are most important in regulating biomass. This would provide a considerable savings in time and money in the application of the HSI. Another criticism is that the development of suitability curves is somewhat subjective, particularly if the variable of interest is difficult to quantify accurately or instrumentation to measure it is lacking.



Percent pools during the late growing season low water period



Average annual base flow regime during the late summer or winter low flow period as a percent of the average daily flow

Figure 1/ Examples of suitability index (SI) curves for two variables, average annual base flow reigme during low flow periods and percent pools, for riverine brook trout populations.

Table 7: Parameters included in the HSI model for brook trout (Raleigh 1982)

Physical	Chemical
Maximum summer temperature	Minimum dissolved oxygen
Maximum water temperature during embryo development	Maximal or minimal pH
Thalweg depth	
Water velocity	
Instream cover	
Substrate size class for fry and small juveniles	
Substrate type in riffles	
Pools during late growing season	
Rooted vegetation and stable rocky ground cover along stream bank	
Base flow regime	
Fines in riffle and spawning areas	
Stream shading	

HSI models consider the habitat requirements of all life stages of fish (eg. embryo, fry, juvenile, adult) and have been developed for many species of warmwater (Stuber 1982; Stuber *et al.* 1982a,b) and coldwater fish (Raleigh 1982; Raleigh *et al.* 1984, 1986), but few have been tested with field data (Terrell 1984). These models were not originally intended to predict standing crops of fish, but to serve as a relative indicator of habitat suitability for a given species. Wesche *et al.* (1987a) tested the HSI model for brown trout (Raleigh *et al.* 1986) and modified the model to develop some predictive capabilities for southeastern Wyoming streams. The Suitability Index (SI) graphs of Raleigh *et al.* (1986) were recalibrated to the study sites as outlined by Li *et al.* (1984) and results of the model were compared with results using the published SI graphs.

The HSI model prediction was not significantly correlated with brown trout standing stock. The HSI component for water quality was significantly related, but its predictive ability was low. Site-specific recalibration of SI curves did not improve the performance of the HSI model. When the nine variables (Table 8) that were significantly correlated with standing stock of brown trout were used in a multiple regression, average annual base flow as a percentage of average annual daily flow and the modified trout cover rating (MTCR) accounted for 52% of the variation in trout standing stock ($R^2 = 0.52$; $P=0.003$). Models with additional variables did not improve the predictability of trout standing stock.

Average annual base flow as a percentage of average annual daily flow was the most significant single predictor of brown trout standing stock (r^2 = 0.36). When regressed against standing stock, the rating of fishing pressure was a significant predictor (r^2 = 0.16) of standing trout stock.

Table 8: Environmental variables analyzed for relationships with brown trout standing stock (Wesche *et al.* 1987). Variables in bold were significantly correlated (α=0.05) with trout standing stock. Superscripts give reference that describes computation of the variable.

Physical	Chemical
Average maximum water temperature[R] (°C)	Average dissolved oxygen[R] (mg/L)
Maximum water temperature during embryo development[R]	Maximal pH[R]
Average thalweg depth[R] (m)	Nitrate nitrogen[R] (mg/L)
Average depth[D]	
Coefficient of variation of stream depth[H]	
Average stream width[P]	
Coefficient of variation of stream width[H]	
Width depth ratio[P]	
Cross-sectional velocity[P]	
Rated cross-sectional velocity[W2]	
Coefficient of variation of cross-sectional velocity[H]	
Time-of-travel velocity[B]	
Average water velocity over spawning areas[R]	
Percent cover during the late growing season low-water periods[R]	
Gradient and sinuosity[P]	
Average diameter of substrate components in spawning areas[R]	
Percent of substrate components 10-40 cm in diameter[R]	
Dominant substrate type[R]	
Rubble substrate[W]	
Rubble substrate at depth ≥15 cm[W]	
Deep-water habitat >45 cm[W]	
Overhead bank cover[W]	
Rubble-boulder cover[W]	
Trout cover rating for small streams[W]	
Trout cover rating for large streams[W]	
Modified trout cover rating[W2]	
Rating of late-summer stream flow[B]	
Rating of average stream flow variation[B]	
Mean stream flow variation[B]	
Average annual base flow as a proportion of average daily discharge[R]	
Shade[R]	
Percent pools[R]	
Average percent vegetation[R]	
Average percent rooted vegetation[R]	
Aquatic vegetation[B]	
Average annual base flow as a percent of average annual flow[R]	
Pool class rating[R]	
Percent fines[R]	
Percent of stream area shaded[R]	

[B] Binns and Eiserman 1979
[H] Hermansen and Kreg 1984
[P] Platts *et al.* 1983
[R] Raleigh *et al.* 1984
[W] Wesche 1980
[W2] Wesche *et al.* 1987

Pajak and Neves (1987) developed an HSI value for rock bass (*Ambloplites rupestris*) using available SI curves and investigated the relationship between HSI value and seasonal standing stock, biomass, and production in fourth-order warmwater streams in Virginia. A consistent correlation between HSI and mean standing stock for the study year was observed only for the largest test reach (250 m), while HSI explained no more than 22% of the variation in standing stock of rock bass in 50 m test sections. Factors implicated in these poor correlations were geographical homogeneity of habitat, seasonal fish movements, and lack of potentially important variables, such as stream depth and cover, that were not included in the HSI models.

Layher (1983) developed separate models to predict standing crops for eight warmwater fish species using data collected at 420 sites in Kansas streams. Independent variables were converted to HSI index values. The best regressions were significant for all species ($P<0.05$), and except for the green sunfish model, all accounted for ≥90% of the variation in standing crop. These same models when applied to data from 50 sites in Oklahoma exhibited low predictive capacity and were not significant. New models were developed for Oklahoma conditions using the same HSI models, but the habitat variables found to significantly influence fish biomass were different. The author concluded that attempts to develop models for large geographical regions were impractical unless species had restricted habitat requirements.

3.3.2/ Habitat Evaluation Procedures (HEP)

The U.S. Fish and Wildlife Service (USFWS) developed Habitat Evaluation Procedures (HEPs) (USFWS 1980a,b, 1981) to predict habitat quality for fish and wildlife from Habitat Suitability Index (HSI) models. HEP is a method which can be used to document the quality and quantity of available habitat for a selected wildlife species. HEPs provide information for two general types of wildlife habitat comparisons:

1) the relative value of different areas at the same point in time (spatial); and
2) the relative value of the same area at future points in time (temporal).

By combining the two types of comparisons, the impact of proposed or anticipated land and water use changes on wildlife habitat can be quantified.

The HEP is based on the assumption that habitat for selected wildlife species can be described by a Habitat Suitability Index. This index value is multiplied by the area of available habitat to obtain Habitat Units (HUs), which are used in the temporal and spatial comparisons of habitat value. The reliability of HEP and the significance of HUs are directly dependent on the ability of the user to assign a well defined and accurate HSI value to the selected species.

HEPs may be used in three distinctly separate, but related, planning activities:

1) wildlife habitat assessments, including both baseline and future conditions;
2) trade-off analyses; and
3) compensation analyses.

The recommended method of describing HSI index values is through the use of HSI models. An HSI model may be in word or mathematical format but, regardless of the format, the model must clearly describe the rules and assumptions used to calculate the HSI. The process of calculating an HSI involves:

1) establishing HSI model requirements;
2) acquiring an HSI model; and
3) determining an HSI value for available habitat

Compensation studies identify measures that would offset unavoidable HU losses due to a proposed action. Compensation occurs by applying specified management measures to existing habitat to effect a net increase in HUs. The existing habitat may or may not be located in the "impact" study area. In order to obtain compensation, the HU losses due to the proposed action must be fully offset by the specified acquisition and/or management measures.

The compensation study must have specific objectives and defined management goals. One specific objective should be to identify a list of target species for which habitat gains can be used to offset habitat losses. The list of target species does not have to be identical to the list of impacted species. The target species are partially determined by the specified compensation goal. Essentially there are three possible compensation goals:

1) In-kind (no trade-off) - precisely offset the HU loss for each evaluation species
2) Equal replacement (equal trade-off) - precisely offset the HU losses through a gain of an equal number of HUs
3) Relative replacement (relative trade-off) - a gain of one HU for a target species is used to offset the loss of one HU for an impacted species at a differential rate depending on the species involved.

3.4/ Instream Flow Incremental Methodology (IFIM)

The Instream Flow and Aquatic Systems Group (IFASG) of the U.S. Fish and Wildlife Service (USFWS) developed a set of physical-habitat models designed for use with the Instream Flow Incremental Methodology (IFIM). The ideas and concepts within the IFIM framework can be used to determine the effects of stream regulation on the instream habitat of fish and invertebrates. The IFIM is considered by some people to be "the most scientifically and legally defensible method available for most instream flow problems" (U.S. Department of the Interior 1979). It is also one of the most widely used methods in North America for estimating the effect of change in flow on trout habitat (Conder and Annear 1987). Physical Habitat Simulation (PHABSIM) is the software portion of IFIM which predicts available habitat in a stream reach under a given set of hydraulic conditions. Hydraulic models are used to predict the main physical variables of the model: water depth, velocity, and substrate within cells of a relatively small stream area (microhabitat), as functions of flow. The substrate parameter may be expressed as a channel index encompassing cover availability, dominant particle size, subdominant particle size, embeddedness, and fines as variables. The area of each cell is multiplied by SI curve index values of the desired fish species for depth, velocity, and substrate at a given flow. Values for all cells in the stream reach are summed to determine the Weighted Usable Area (WUA). Several variables (eg. depth, velocity) have been

described for fish species and recent IFIM procedures may also incorporate a cover preference variable.

IFIM has several inherent assumptions:

1) Fish respond in a predictable manner to average water velocities estimated for each cell by the hydraulic models.
2) A large area of suboptimal habitat is equivalent to a smaller area of optimal habitat.
3) The fish population is primarily limited by suitable habitat (temperature and water quality) and microhabitat, not by food, competitors, predators, or fishing mortality.
4) Fish/benthos exhibit discrete and quantifiable preferences (as habitat suitability curves from HSI) for a range of velocities, depths, substrates, etc.
5) Depth, velocity, and substrate are assumed independent in some preference functions for a given target species.
6) A positive linear relationship exists between WUA and physical habitat, and a relationship exists between physical habitat and standing crop.
7) The habitat is at its maximum carrying capacity for the species in question.

Many of these assumptions are based upon engineering principles and have not been tested biologically under lab or field conditions. Critiques of the IFIM suggest that several assumptions are violated in the application of IFIM without consideration of the subsequent implications (Mathur *et al.* 1985). The fundamental assumption that a positive linear relationship exists between WUA and fish biomass has neither been documented or validated, particularly in warmwater streams. Violation of this assumption precludes the use of the model in a predictive capacity. Another assumption that was violated was the independent selection of habitat variables by fish. Also, under southern Ontario conditions, one cannot assume that the fish population is limited primarily by suitable habitat since many areas receive tremendous angling pressure. In addition, Bowlby and Roff (1986) have shown that predation (the presence of piscivorous fish) significantly affected trout biomass. The IFASG and other researchers are presently working to validate these assumptions and develop models addressing and incorporating many of these assumptions and variables.

WUA has been used as an independent variable to predict fish standing crop with equivocal results. WUA accounted for 81-82% of the variation in brown trout biomass in Wyoming streams (Stalnaker 1979 - data from Wesche 1976; Wesche 1980). WUA at average discharge was highly correlated with brown trout biomass in Colorado streams, but not with brook or cutthroat trout biomass (Nehring 1979). The latter low correlations were attributed to fair SI curves for brook and cutthroat trout, while SI curves for brown trout were good to excellent. Annear and Conder (1983) found low correlations between WUA and biomass of brown and rainbow trout in Wyoming streams. Orth and Maughn (1982) found WUA to be significantly correlated with standing crop of freckled madtom, orangebelly darter, and central stoneroller, but not smallmouth bass in Oklahoma streams. Correlations were highest during summer when habitat was assumed to be most limiting to stream fish due to low flow conditions. Loar *et al.* (1985) tested the capacity of WUA to predict standing crops of brown and rainbow trout in southern Appalachian streams of Tennessee and North Carolina. Although a significant correlation was evident for brown trout ($r=0.84$, $P<0.05$), no relationship was found for rainbow trout, possibly due to sympatric effects of competition from brown trout. Analysis of allopatric rainbow trout populations revealed several significant correlations with WUA.

A second validation approach, termed the "within-stream" approach, was examined by Conder and Annear (1987). This technique tests the assumption that, for an individual stream, changes in WUA reflect changes in habitat and standing crop with changes in discharge. Orth and Maughn (1982) observed a significant correlation ($P<0.05$) between standing crop and WUA in only 30% of tests, while Shirvell and Morantz (1983) found a negative within-stream relationship between WUA and the density of juvenile Atlantic salmon (*Salmo salar*). In contrast, Gowan (1984) observed that 83% and 90% of the variation in brook and brown trout abundance, respectively, in a Michigan stream was explained by the WUA calculated for the average daily flow measure of the previous two weeks during the summer. Conder and Annear (1987) tested this assumption by investigating the relationship between WUA and standing crop (as predicted by HQI). They found definite species effects, with a strong positive correlation between WUA and fish biomass in 80% of streams dominated by rainbow trout, but only in 40% of the

streams dominated by brown trout. In general, the validity of the within-stream relationship between WUA and the trout standing crop predicted by the HQI, was influenced by trout species, stream size, and stream gradient.

The on-site development of SI curves for fish/benthos and measurement of microhabitat variables for fish (Moyle and Baltz 1985) appear to be necessary to provide the most accurate predictions for the model. In other words, site-specific calibration of the model is necessary for reasonable predictive capacity. Regardless of on-site development of SI curves or model calibration, if model assumptions are violated, the use of these models is often unjustified.

4/ Habitat Classification Systems

No true experts systems relating fish production to habitat were found in the literature. There are, however, a number of classification systems and screening procedures that may be of use in the development of an expert system or in conjunction with existing mathematical models.

4.1/ Stream Classification

Rosgen (1985) developed a stream classification system according to stream "channel types" based on morphological channel features. Each channel type or sub-type has characteristic patterns that are developed and maintained by geomorphological and hydrological factors. If variables responsible for these patterns (eg. velocity, depth, width, substrate, obstructions, sediment) are altered, adjustments occur between these variables to achieve a balance or "equilibrium". Applying these principles may allow the manipulation of the correct habitat variables in designing compensation works. This stream classification system may also be used in the development of an expert system. Classification of streams prior to production or biomass model development would likely increase the precision and predictive capacity of the models.

4.2/ TransCanada Pipeline Screening Procedure

TransCanada Pipeline developed a habitat screening procedure that allows the identification of "sensitive" and "non-sensitive" fluvial crossing areas for pipelines. Initial screening involves a search of available technical, historical, and habitat information for the site in question. Once a decision has been reached regarding the necessity of on-site reconnaissance, a habitat assessment is conducted using modified HSIs for various fish species. A composite warmwater and coldwater habitat evaluation is employed. If critical habitat is identified, then the potential for downstream sediment transport during crossing construction is assessed. This screening procedure may provide a foundation for the development of an expert system addressing fish habitat concerns with regard to construction works.

4.3/ Rapid Biomonitoring Assessment Protocol

The Rapid Biomonitoring Assessment Protocol (RBP; Plafkin *et al.* 1989) was designed by the U.S. Environmental Protection Agency as a means of conducting cost-effective biological assessments of lotic systems. There are procedures (RBP I-V) that provide varying levels of information on macroinvertebrate and fish community structure ranging from screening procedures to more rigorous procedures to provide confirmational data. Although designed for assessing population responses to pollution sources, many portions of these procedures would be extremely helpful in the development of an expert system.

5/ Overview of the Fausch *et al.* 1988 Model Review

Fausch *et al.* (1988) conducted a detailed review of models that relate environmental variables to fish production or biomass in streams. The models were organized by types of habitat variables found significant, mathematical structure, size of the data set used to develop the models, and how well the models fit the data. To facilitate future model development, statistical methods, errors in habitat measurements, and major biological assumptions of the models were critically assessed. All models found in the primary literature, reports of State and Federal natural resource agencies, theses, abstracts (Sport Fishery Abstracts), and personal sources were reviewed. Fausch *et al.* (1988) reported that most models were found through personal communication with fisheries biologists, with relatively few published in primary fishery or aquatic biology journals. An overview of their review is provided here as a useful comparison with our findings.

Model variables were divided according to method and scale of measurement. **Drainage basin** variables (area, mean basin elevation, stream gradient, total stream length) were measured from topographical maps. **Channel morphometry and flow** variables (width, depth, stream discharge, velocity) could be measured in the field along transects of a flow. **Habitat-structure, biological, physical**, and **chemical** variables, including instream and bank cover, invertebrate drift abundance, substrate, and temperature, were related to fish microhabitat within a stream reach. Many of the variables in this class, especially some of the cover and substrate variables, are often difficult to measure and standardize since they are based upon subjective evaluation.

Models were classified into five categories according to the major types of independent variables significantly related to fish biomass. The model categories are listed below:

1) Drainage basin
2) Channel morphometry and flow
3) Habitat-structure, biological, physical, and chemical
4) Variables from all the type-groups
5) Weighted Usable Area (WUA; Bovee 1982)

Simple or multiple linear regressions were the most common model types evaluated. Regression models are advantageous since standard statistical procedures may be used to calculate regression coefficients, confidence limits and prediction bands around the regression line, and the percentage of variation in standing crop explained by particular independent variables. Some models combined independent variables into one or more indices and then used regression to calculate a function between standing crop and the index. Multivariate statistical techniques of factor analysis or principal-components analysis were used in some models to select linear combinations of variables to explain most of the variation in standing crop and reduce the number of variables in the data set. The relative quality of best models from each study were assessed according to coefficient of determination (r^2, or R^2 for multiple linear regression) and sample size (≥20 or <20).

Category I: ***Drainage basin models***

Models relating drainage basin variables to fish production will not be reviewed in great detail in this report. Although drainage basin variables related to fish production should be considered to better understand the "big" picture in fisheries management of a given river, instream construction works are usually restricted to smaller, more defined reaches within a watershed. Although instream works may not directly affect the fish production of a stream, the entire construction works (eg. 40 km of highway) in a given watershed should be considered as it may cause significant alterations in hydrological features such a groundwater recharge.

The basic premise of these models is that certain drainage basin characteristics (eg. geomorphology) are related to flow regime and channel morphology which in turn control fish production (Lanka *et al.* 1987; Lanka 1985; Ziemer 1973). Fausch *et al.* (1988) proposed that this category of models would be most useful for basin-wide planning and analysis in fishery management since they appeared relatively imprecise based solely on coefficients of determination. However, Lanka (1985) found relative prediction errors of 39% for the best model for rangeland streams, and only 18% when the model was tested. Drainage basin models were also used to separate good and poor spawning streams for

Pacific salmon in Alaska by using discriminant functions (Swanston *et al.* 1977), and to predict habitat quality for anadromous salmonids in Oregon under natural and managed conditions (Heller *et al.* 1983; Parsons *et al.* 1981). Jowett and Duncan (1990) employed univariate and discriminant analyses to determine that the most important hydraulic variable in New Zealand watersheds was water velocity, which could be linked directly to changes in water temperature, benthic invertebrate and periphyton community structure, and trout distribution and abundance.

Category II: ***Channel morphometry and flow variables***

Standing crops and production of fish have been significantly correlated with a variety of channel morphometry and flow variables, such as stream width, depth, discharge, overhead bank cover, and velocity. Pool area and bank cover together explained 68% of the variation in numbers of brook trout larger than 6 inches after a stream habitat enhancement program in Wisconsin (Hunt 1971). Overhead bank cover, provided primarily by riparian vegetation, explained the greatest amount of variation in trout standing crop in Wyoming streams (Wesche *et al.* 1987b).

Baseflow discharge explained 71-74% of the variation in numbers of fall young-of-the-year (YOY) brook trout using 9 years of data for a Michigan stream, but accounted for relatively little of the variation in abundance of YOY brown trout (Latta 1965). Analysis of 17 years of data for the same stream found no significant relationships between abundance of YOY brook trout and flow variables, although a multiple regression of YOY brown trout numbers on flow variables explained 37% of the variation (White *et al.* 1976). Burton and Wesche (1974) found that streams with higher base flows during the summer supported significantly greater brown trout standing stocks. Significant positive relationships were reported between stream salmonid populations and elevated water flows for brook trout (Hunt 1979; White 1975), brown trout (Solomon and Paterson 1980; Hunt 1979) and Atlantic salmon (Frenette *et al.* 1984). However, extremely high water flows during critical life stages such as incubation and fry emergence may reduce year class sizes (Nehring and Anderson 1981, 1982, 1983, 1984). Jowett (1990) noted that brown and brook trout distribution in New Zealand rivers was related to water

temperature, geographical, and hydrological factors, while trout abundance was determined by flow variability, river gradient, in-stream habitat, and the presence of lakes in the catchment. Field measurement of channel-morphometry and stream flow variables resulted in an increase in model precision, relative to drainage basin models, based solely upon coefficients of determination.

Category III: ***Habitat structure, biological, physical, and chemical variables***

Chemical variables, especially those related to water hardness, may be related to fish production or biomass. The partial correlation between non-salmonid biomass and conductivity accounted for the most variation in production in six Pennsylvania streams (McFadden and Cooper 1962). Fish production was much higher in English streams high in calcium, even though most of the extra production was contributed by non-salmonid species (Le Cren 1969). A single overhead bank cover variable explained 88 and 93% of the variation in brook trout biomass in two Michigan streams (Enk 1977; Wesche 1974). Wesche *et al.* (1987b) also found that overhead bank cover was a significant predictor of trout standing stock in streams of southeastern Wyoming dominated by brown trout. Other authors also found significant positive relationships between cover variables and salmonid density or biomass (Gordon and MacCrimmon 1982; Harshbarger and Bhattacharyya 1981; Ward and Slaney 1980; Wesche 1980; Klamt 1976). Fausch *et al.* (1988) suggest that these studies indicate that many forms of cover can significantly affect stream populations of salmonids when other factors are not limiting.

Stream substrate is often used as a variable to predict standing crop of fish in a stream reach. The abundance and biomass of smallmouth bass in an Iowa river was a function of the percentage area of exposed substrate of 16-256 mm (Paragamian 1981). Evaluation of the effectiveness of several habitat quality indices (Binns 1979; Duff and Cooper 1978; Plankuch 1975) at predicting trout standing crop suggested that the best model was based upon the area of substrate composed of rubble, boulder, or aquatic vegetation (Eifert and Wesche 1982). Stowell *et al.* (1983) found that fry emergence and rearing capacity for juvenile steelhead and chinook salmon could be predicted in Idaho rivers from the percentage embeddedness of the stream substrate. All models that

include measures of substrate indicate that stream fish are dependent on specific substrates for spawning and for hiding cover for juveniles and adults.

Models based primarily on habitat-structure, biological, physical, and chemical variables require the most effort to apply since field measurement of these variables is generally time consuming. More precise models appear to be limited in their general applicability since they apply to specific streams or life stages of fish that are limited by few environmental variables.

Category IV: ***Combinations of variable types***

This category includes models which use variables of the three previous model types. Nickelson *et al.* (1979) developed a Habitat Quality Rating (HQR) composed of the summed frequencies of suitable depths, instream cover, overhanging cover, surface turbulence, and velocity refuge, measured at points along stream transects, which was multiplied by a factor reflecting the suitability of section velocity for cutthroat trout and by section area. Used as an independent variable to predict standing crop, the HQR accounted for 87-91% of the variation of the standing crop of cutthroat trout.

Models developed by Hendrickson *et al.* (1973a) suggested that standing crops of trout in Michigan and Wisconsin streams is related to high ground water discharge and water hardness. Power (1973) explained variations in the production of Arctic charr (*Salvelinus alpinus*), brown trout (*Salmo trutta*), and Atlantic salmon (*Salmo salar*) in northern Norwegian rivers by the sediment composition of stream bottoms, stream width, presence or absence of glacial silt, and land-use characteristics of the river valleys. Scarnecchia (1983) explained 60-84% of the variation in trout production and 60-75% of the variation in biomass in Colorado headwater streams using elevation, width-to-depth ratio, substrate diversity, nitrate, and sulfate.

Many of the models in this category require quantification of a large number of variables which are often difficult to measure accurately. These types of models may be prohibitively expensive unless variables are easily measured, data are available, or the

costs involved for a specific fishery are justified. Fausch *et al.* (1988) concluded that these types of models would only be useful when applied to specific situations and geographical regions, and not on a general scale.

Category V: ***Weighted Usable Area (WUA)***

A complete discussion of the relationships of WUA with fish biomass or production, and its assumptions and problems was provided in the Section 3.4 on IFIM procedures.

5.1/ Assessing Model Quality and Important Habitat Variables

Fausch *et al.* (1988) suggested that ideal models to predict standing crops of fish in streams would include all the important functional aspects of fish populations; account for a large percentage of the variation in standing crop and be reproducible; and retain generality by incorporating data from a broad geographical area and retaining at least 20 error degrees of freedom after fitting model parameters.

Model precision and generality were assessed using simple criteria such as coefficients of determination, sample size, and degrees of freedom. Of the 98 models reviewed that reported sample size, 39 were from developed from data sets with ≥20 observations, but only 18 of these models explained ≥75% of the variation in standing crop. However, 68% of models developed from data sets with ≤20 observations explained ≥75% of the variation in standing crop. Where data was available, only 33% of the models developed had ≥20 degrees of freedom, and only 48% of these models explained ≥75% of the variation in standing crop. Of the models with <20 degrees of freedom, 67% explained ≥75% of the variation in standing crop. The authors concluded that most relatively precise models arise from data collected over short time periods (≤one year) or small geographic areas (single stream or watershed) and thus lack generality. Another general criticism regarding model development was that very few modellers or researchers actually tested their models on other data sets.

When models were grouped according to sample size, coefficient of determination, and the five categories of variables, they found that the majority of models with the larger sample sizes (>20) and larger coefficients of determination (>0.50) used a combination of variable types. The seven variables most often significantly related to standing crop in the 85 models reviewed were: measures of instream overhead cover, depth, alkalinity/hardness/conductivity, mean stream flow, width, surface area, and dissolved oxygen. The authors also suggested that this analysis may be biased since investigators often used data at hand or evaluated easily measured variables.

Fausch *et al.* (1988) observed that sound sampling or statistical procedures were often minimized during model development and suggested that data collected from only a few years or from a few streams do not allow strong inferences to be made regarding habitat variables across years or in areas outside the bounds of the defined population. In other words, these models lack generality. Modellers were encouraged to seek the advice of knowledgeable statisticians during the project planning phase. Through this type of consultation, researchers can select proper statistical techniques to assess autocorrelation among independent variables, estimate model parameters, and analyze residuals to test model assumptions and fit.

A number of problems common to many of the models were also noted. **Sample sizes** were often too small (N<20), either with too few dates of sampling or too few locations to encompass normal variation in fish populations. Problems were also evident in **measuring habitat variables**. A basic assumption of most procedures used to fit linear regression models is that the independent variable is measured without error (Sokal and Rohlf 1981). This assumption is often violated during the measurement of stream habitat variables, so variance of the independent variable must be considered in the model. Platts (1981) and Platts *et al.* (1983) made repeated measurements in the same areas of streams over a period of 7 years. They found that the most precise variables were those that could be estimated objectively using an instrument (eg. width, depth) while subjective variables (eg. % of a certain substrate) judged visually were much less precise. Bias was due to different observers and to the natural changes in habitat features over

time. The accurate estimation of the dependent variable (standing crop of fish or production) may also be difficult and assumptions may be violated. Relatively few researchers **tested or validated** their models to determine whether they were accurate at another time or place. Models that combine habitat variables into complex products or indices (Binns and Eiserman 1979; Nickelson *et al.* 1979) are difficult to assess since it becomes difficult to determine whether they accurately reflect the functional response of fish to habitat. WUA has been tested for a number of fish species, but most tests were conducted with relatively small sample sizes. These tests have helped define data needs for habitat suitability criteria (Bovee 1986). Although many authors report a significant regression and a coefficient of determination for regression models, they neglect to include confidence bands on the regression, thus precluding its use in a predictive capacity. Authors should supply the standard error of regression and the ranges of values measured for each habitat variable and caution not to extrapolate outside these ranges. Models usually pertain to specific geographic areas and may have poor predictive capabilities, even in nearby areas. When data are observational rather than experimental, statements about data other than those observed is difficult. Since habitat variables cannot be easily controlled or manipulated, changes in habitat variables cannot be considered to have caused changes in the standing crop of fish. Instead, variables related significantly to standing crop may only be surrogates for other unmeasured variables that directly affect fish populations.

All models assume that the fish population is limited by the set of habitat variables included in the model. Few authors address whether fishing pressure, interspecific competition (Li *et al.* 1984; Loar *et al.* 1985), or predation (Bowlby 1986) might actually be limiting the standing crop below levels that the habitat could support. In order to construct accurate models, these issues must be addressed. Some models are based on data obtained from areas that were specifically selected since they received low fishing pressure. Extrapolation from models developed using these populations to areas that are significantly affected by anthropogenic activities is difficult.

From the 85 models reviewed by Fausch *et al.* (1988), 183 environmental variables were significantly related to fish biomass or production (Appendix B). Many of these variables are measures of the same parameter (eg. water hardness) but are expressed in different ways by different researchers. There has been a suggestion for standardization in the measurement of environmental variables (Mullan 1983; Platts 1983; Wesche 1983). When similar variables were grouped together (Appendix C), the seven most frequently significant and their occurrence in models were: instream overhead cover (22), depth (20), alkalinity/hardness/conductivity (15), mean stream flow (14), width (14), surface area (12), and dissolved oxygen (11). Each of these variables was also found significant in one or more of the models with $r^2 > 0.50$ and ≥ 20 degrees of freedom. This analysis is somewhat biased since many modellers used available data or easily measured variables.

Fausch *et al.* (1988) also presented some recommendations for making these models useful for fisheries managers:

1) Models must include variables that can be manipulated by managers, eg. instream cover

2) Model precision could be improved by stratifying lands into homogenous ecoregions, particularly for the more general models. Lanka (1985) found that model performance in predicting biomass could be increased by the separation of basins into homogenous groups prior to analysis. Although the classification of Lanka (1985) was according to drainage basin elevation, other classification systems may also prove useful.

In summary, Fausch *et al.* (1988) stressed the need for experiments to test hypotheses regarding mechanisms underlying the responses of fish populations to habitat variables. For habitat variables that cannot be manipulated, rigorous cycles of statistically sound model building and testing are needed in various geographical regions to develop an understanding of the mechanisms that govern fish production. The benefits of these two approaches will be an enhanced knowledge of underlying theory on which to base sound fishery and habitat management, and perhaps the development of models with greater predictive capacity.

6/ Evaluation of Models

Characteristics of the models reviewed in this study are presented in Table 9. All the mathematical models reviewed were more descriptive than empirical in nature. The HQI was developed in Wyoming, and is the only model that may not be applicable to southern Ontario conditions. The other models were either developed in Ontario (OTHC) or have been used in all areas of the United States (HSI and IFIM). The HQI and OTHC utilize multiple regression and discriminant function analyses, respectively, using standard statistical software. The HSI is a index rating system, and is incorporated into the IFIM methodology. Some degree of fisheries expertise is required for the implementation of all models. The capacity of the models to predict fish biomass or production is limited by the lack of testing of the models and validation of associated assumptions. Stream classification according to geomorphological characteristics (Rosgen 1985) has the potential to increase model precision and to facilitate the development of expert systems. Fish habitat classification indices, such as the TransCanada Pipeline Screening Procedure and the RBP (Plafkin *et al.* 1989), are used for rapid screening to determine which fish habitats are sensitive to anthropogenic perturbations, and may be used in the development of expert systems.

Table 9: Summary of models reviewed, their characteristics, and potential applications.

Model	Region study conducted	Applicability to southern Ontario	Type of Model and Output	Expertise required	Potential use	Comments, problems, limitations
HQI	Western US (Wyoming)	No	Multiple regression Descriptive Expected standing crop	Fisheries	Limited	Must be calibrated to each system
HSI	USA	Yes	Index Descriptive	Fisheries	Used to identify fish habitat	Encompasses many warmwater and coldwater species; includes requirements of different life stages in model
OTHC	Southern Ontario	Yes	Multiple regression and discriminant analysis Descriptive	Fisheries Statistics	Identify parameters that influence fish biomass	Must be calibrated to each system

Table 9: Summary of models reviewed, their characteristics, and potential applications.

IFIM	USA	Yes	Descriptive	Fisheries	Qualitative predictions of habitat quality under hypothetical flow regimes	Assumption: Positive linear relationship between potential available habitat (WUA) and fish biomass (not documented or validated)
TCP screening	Canada	Yes	Decision tree Classification Index	Limited fisheries	Screening procedure for determining "sensitive" areas; Habitat classification	Uses HSI approach Both warm- and coldwater
RBP	USA	Yes	Classification Index	Fisheries Biology	Screening to intense assessment of habitat health	Uses Rosgen's stream classification system Adaptable to any lotic system

Based upon our review of the literature, no single model is currently available which offers both generality and precision for the estimation of fish production from environmental variables when applied to a given reach of lotic habitat. We concur with the recommendations of other reviewers, suggesting that site-specific data needs to be collected to estimate fish production in a particular river. In order to develop an approach that would be useful for the MTO in estimating fish production in rivers and also be amenable to the MNR and DFO, we propose the following recommendations for future model development:

1) Investigate increasing the predictive potential of existing models by applying them after lotic habitats have been grouped *a priori* according to some form of classification scheme. Streams may be grouped according to distinct geomorphological characteristics (Rosgen and Fittante 1989; Rosgen 1985; Frissell *et al.* 1986), whether they support warm- or coldwater fisheries, or whether or not fish populations receive angling pressure. A geoclimatic stream habitat classification system has also been proposed for southern Ontario (Portt *et al.* 1989).

2) Attempt to standardize measurement of the more subjective variables currently used in models. Of these subjective variables (eg. % area of a certain type of substrate), many of

them may be measured semi-quantitatively using Geographical Information Systems (GIS) or a similar system, to reduce errors introduced by the subjective measurement of variables. It may also be necessary to decide which variables are the most important in determining fish production, not just those variables that are available or most easily measured and examine in detail the results of models utilizing these variables.

3) Develop a rule-based expert system that incorporates pre- and post-construction assessment of fish habitat structure in a reach of the lotic system in question. The Dichotomous Key for the use of Lake Trout as an Indicator of Ecosystem Health (Marshall *et al.* 1987) is an example of a simple expert system which transfers knowledge from experts to non-experts for the purpose of diagnosis and problem solving. This expert system could be used to assess the impacts of instream works on fish populations and determine what type of compensation, if any, is necessary. The guidelines set out by Rosgen (1985) for the use of stream enhancement structures in river channels of specific types may be applied during the compensation process. Once the instream structures have been placed, the addition of cover structures at strategic locations (eg. logjams, overhead cover) could be introduced to maximize fish production.

4) Adopt the HEPs and/or the IFIM procedure in evaluating habitat compensation situations. They offer the advantage of currently being used in this capacity in the U.S. and there is a wealth of literature on their use. However, many of the assumptions associated with these models have not been validated, and the models should be applied with caution.

In general, any of the above approaches may be acceptable for estimating fish production or biomass from habitat variables, provided that assumptions inherent with each model are addressed. Furthermore, most of the models were developed for resident salmonid populations with low angling pressure. Indeed, a fundamental assumption of IFIM and HSI is that the habitat is at its maximum carrying capacity for a given species. It is unclear how these models would function for anadromous fish stocks or with populations that experience increased mortality associated with angling pressure. Some attempts have been made to determine the response of fish populations to a variety of environmental and

anthropogenic stressors (Munkittrick and Dixon 1989), and perhaps these ideas should be incorporated into subsequent models.

In addressing the second objective of this report, only a few of the environmental variables significantly related to fish biomass or production have the potential to be incorporated into designs by planners/designers of instream works. Variables such as water hardness cannot be changed, but stream depth and width could reasonably be manipulated during design/planning stages. Cover and overhanging riparian vegetation may be added after instream works are completed to enhance habitat usage by fish.

The HQI, OTHC, and IFIM have limited applications to the needs of the MTO, basically due to their relatively complex mathematical nature, a predictive capacity that is not specific enough to meet the needs of MTO, and the fact that many of the assumptions associated with the models have not been validated. The HSI, although validation of assumptions is incomplete, holds some promise in the evaluation of pre- and post-construction lotic habitat, and a modification of the existing model may be of benefit to the MTO.

7/ Summary

Using a slightly different approach and more models, the results and recommendations of Fausch *et al.* (1988) are generally in agreement with the results of our literature review. Fausch *et al.* (1988) stress the fact that sound statistical approaches are often lacking during model development and that little testing of models and their assumptions is conducted. Consequently, it is difficult to apply a given model developed in a specific area/region to fish biomass in any other region. A rule-based expert system that simply decides habitat equivalents for compensation may be an alternative to these models.

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Appendix A/ Extended Summaries of Models Reviewed

Model	Variables	Output
Habitat Quality Index (HQI) - Model I (Binns and Eiserman 1979) Predicts relationship between HQI score and trout standing crop Explained 95% of the variation in trout standing crop (R = 0.977)	$\hat{Y}$ = Predicted trout standing crop (kg/ha) X_1 = Late summer stream flow X_2 = Annual stream flow variation X_3 = Maximum summer stream temperature (°C) $P = X_4(X_5)(X_6)(X_7)(X_8)(X_{10})(X_{11})$ X_4 = Nitrate nitrogen (mg/L) X_5 = Fish food abundance (number/0.1 m^2) X_6 = Fish food diversity X_7 = Cover (%) X_8 = Eroding stream banks (%) X_{10} = Water velocity (m/sec) X_{11} = Stream width (m)	$\log_{10}(Y+1) = [(-1.18257) + (0.97329)\log_{10}(X_1+1) + (1.65824)\log_{10}(X_2+1) + (1.44821)\log_{10}(X_3+1) + (0.30762)\log_{10}(P+1)]$ -[1.12085]
Habitat Quality Index (HQI) - Model II (Binns and Eiserman 1979) Predicts relationship between HQI score and trout standing crop Explained 97% of the variation in trout standing crop (R = 0.983) Replaces fish food abundance and diversity attributes with a substrate attribute, P factor with shelter and food indices	$\hat{Y}$ = Predicted trout standing crop (kg/ha) X_1 = Late summer stream flow X_2 = Annual stream flow variation X_3 = Maximum summer stream temperature (°C) F = Food index = $X_3(X_4)(X_9)(X_{10})$ $S = X_7(X_8)(X_{11})$ X_4 = Nitrate nitrogen (mg/L) X_7 = Cover (%) X_8 = Eroding stream banks (%) X_{10} = Water velocity (m/sec) X_{11} = Stream width (m)	$\log_{10}(Y+1) = [(-0.903) + (0.807)\log_{10}(X_1+1) + (0.877)\log_{10}(X_2+1) + (1.233)\log_{10}(X_3+1) + (0.631)\log_{10}(F+1) + (0.182)\log_{10}(S+1)]$ -[1.12085]

Model	Variables	Output
Habitat Suitability Index Model (HSI) Brook Trout (Raleigh 1982) Model in its present form is not intended to predict standing crops of trout, just serve as a relative indicator of habitat suitability for the species Possibility of calibration model output to reflect standing crop size in site specific situations HSIs are derived from habitat suitability index graphs or curves (HSC) for each variable Model considers five life stage components: Adult, juvenile, fry, embryo, other	V_1 = Average summer maximum water temperature V_2 = Average maximum water temperature during embryo development V_3 = Average minimum dissolved oxygen (mg/L) V_4 = Average thalweg depth (m) V_5 = Average water velocity (m/sec) V_6 = Percent instream cover V_7 = Average size of substrate (cm) V_8 = Percent substrate size class used for winter and escape by fry and small juveniles V_9 = Dominant substrate type in riffle-run areas V_{10} = Percent pools during late growing season V_{11} = Average percent vegetation along stream bank V_{12} = Average percent rooted vegetation and stable rocky ground cover along streambank V_{13} = Annual maximal or minimal pH V_{14} = Annual base flow regime V_{15} = Pool class rating during late growing season V_{16} = Percent fines (<3 mm) in riffle-run and spawning areas V_{17} = Percent of stream shaded	$HSI = [(C_A)(C_J)(C_F)(C_E)(C_O)]^{1/N}$ (C_A) = Adult component (C_J) = Juvenile component (C_F) = Fry component (C_E) = Embryo component (C_O) = Other component N = Number of variables used in the calculation of C_O Each component is calculated according to instructions in the HSI document eg. Adult (C_A) - Variable V_4, V_6, V_{10}, V_{15} Case 1: Where V_6 is $> (V_{10} \times V_{15})^{1/2}$ $C_A = [V_4 \times V_6 (V_{10} \times V_{15})^{1/2}]^{1/4}$ Case 2: Where V_6 is $\leq (V_{10} \times V_{15})^{1/2}$ $C_A = [V_4 (V_{10} \times V_{15})^{1/2}]^{1/4}$ If V_4 or $(V_{10} \times V_{15})^{1/4}$ is ≤ 0.4 in either equation, then C_A = the lowest score.

Model	Variables	Output
Ontario Trout Habitat Classification Model (OTHC) Bowlby 1986 Uses regression and discriminant function analyses to relate trout biomass to biotic and physical habitat variables	**Biotic variables** Abundance and biomass of drift by 3 size classes Abundance and biomass of benthos by 4 size classes Benthic invertebrate size Benthic invertebrate abundance and biomass Sediment microcommunity biomass (ATP) (ng/cm^3) Suspended microcommunity biomass (ATP) (ng/L) Sediment organic matter Suspended organic matter **Physical variables** Maximum and minimum weekly summer temperature Mean maximum and minimum weekly summer temperature Highest minimum weekly summer temperature Mean summer temperature Current velocity at thalweg Width, Depth profile, % pool area % silt, sand, gravel, rubble, boulder, clay, bedrock % organic debris Substrate diversity, Overall substrate diversity % log cover, bank cover, brush cover % aquatic vegetation cover, rock cover Cover diversity, Overall cover diversity	HQI models (Binns and Eiserman 1979) performed poorly in predicting trout biomass in southern Ontario streams Covariance matrices and vectors containing means that act as "coefficients" in the quadratic discriminant function model Results indicate that trout biomass in southern Ontario streams is significantly ($P<0.05$) correlated with suspended microcommunity biomass (ATP of suspended solids), pool-overhead cover, mean maximum summer temperature, maximum summer temperature, % vegetation instream cover, presence of piscivores

Model	Variables	Output
Instream Flow Incremental Methodology (IFIM) (Bovee 1982, 1986) Developed to quantify fish habitat changes under different flow conditions Not useful to predict fish populations in streams since no attempt is made to derive relationship between fish density and habitat quality Physical Habitat Simulation (PHABSIM) software portion of IFIM which predicts available habitat in a stream reach under a given set of hydraulic conditions Assumption: Fish/benthos exhibit discrete and quantifiable preferences (as habitat suitability curves from HSI) for a range of velocities, depths, substrates, etc. Relationship between available habitat, expressed as Weighted Usable Area (WUA), and altered flow regimes can be determined On-site development of HSCs for fish/benthos yields most accurate predictions	Stream depth Stream velocity Channel index (cover availability, dominant particle size, subdominant particle size, embeddedness, percent fines)	$F[v,d,s] = f(v) \times g(d) \times h(s)$ $F[v,d,s]$ = function that combines information on velocity, depth, and channel index into a single composite value for a target life stage $f(v)$ = function that transforms stream velocity (v) into a measure of value for a target life stage $g(d)$ = function that transforms depth (d) into a measure of value for a target life stage $h(s)$ = function that transforms channel index (s) into a measure of value for a target life stage These functions are usually presented as suitability curves (see HSI) $WUA = \Sigma\ F[f(v_i), g(d_i), h(s_i)]\ a_i$ WUA = Weighted Usable Area, a_i = area

Appendix B/ Independent Variable Found Significant in the Best Models
(from Fausch *et al.* (1988))

Variable	Variable
Drainage Basin	
Annual rainfall	Man basin length
Basin perimeter	Mean basin slope
Drainage area	Elevation rating
Distance from Atlantic Ocean	Gradient rating
Drainage density	Mean basin elevation rating
Reach elevation	Relief ratio
Forested area	Stream order
Reach gradient from map	Total stream length
Mean basin elevation	Watershed condition
Channel Morphometry	
Area of deep water >1,5 ft	Minimum width rating
Channel width at bankful flow	Percentage of pool rating
Frequency of depth 46-60 cm	Percentage of riffle rating
Frequency of depth > 60 cm	Percentage of run rating
Mean depth	Stream width rating
Mean pool depth	Riffle width
Mean width	Rating of width-to-depth ratio
Pool area	Maximum width rating
Percentage of pool	Surface area
Percentage of riffle	Section gradient measured in field
Pool volume	Channel volume
Pool width	Width-to-depth ratio
Riffle area	Maximum depth
Mean depth rating	Maximum pool depth
Mean width rating	
Flow variables	
Annual flow variation	Mean spring flow
Critical period flow as percent of mean flow	Mean velocity
	Mean winter flow
Flow	Minimum summer flow
Flow 11 days previous	Minimum spring flow 1 year previous
Difference between 7-day maximum and 7-day minimum winter flows 3 years previous	Minimum spring flow 2 years previous
Mean flow per unit area	Annual flow variation rating
	Late summer flow rating

Mean flow per unit area
Mean monthly flow
Mean pool velocity
Mean summer flow
Mean summer flow 2 years previous
Velocity rating
Velocity index
Maximum pool velocity
Maximum summer flow
Maximum summer flow 1 year previous
Maximum spring flow

Habitat Structure

Area of aquatic vegetation
Area of all cover
Area of overhanging riparian vegetation
Area of overhanging riparian vegetation >1m above water
Area of overhanging riparian vegetation 1-2 m above water
Area of rubble, boulder, and aquatic vegetation substrate
Area of undercut bank
Area of water willow
Bank stability rating
Channel debris
Deep slow area
Frequency of cover in water >5 cm deep
Frequency of turbulence in water >5 cm deep
Frequency of turbulence in water >5 cm deep
Frequency of velocity refuge in water >5 cm deep
Rating of eroding banks
Shallow slow area
Length of undercut bank
Number of rocks
Number of rocks > 30 cm
Percentage of area as cover
Percentage of area as aquatic vegetation
Percentage of pool area as bruch cover
Percentage of area as boulder and log cover
Percentage of eroding bank
Pool feature
Percentage of area as instream bank vegetation
Percentage of area as instream cover
Percentage of zero velocity
Pool rating
Pool turbulence cover
Root cover <0.1 m^2
Root cover >0.3 m^2
Rating of cover
Streambank condition
Total cover rating

Biological

Days from June 1
Depth and velocity preference factors
Estimate of eggs deposited
Invertebrate drift abundance
Species range
Number of fish species
Preference factor for rubble, boulder, and aquatic vegetation
Preference factor for undercut bank
Previous standing crop

Physical - Substrate

Area of boulder substrate	Percentage of gravel substrate
Area of cobble substrate	Percentage of rubble substrate
90th percentile substrate size	Percentage of fine sediment <1 mm
Mean riffle particle size	Percentage of area of 16-256 mm substrate
Percentage of boulder substrate	Substrate rating
Percentage of substrate embeddedness	Area with suitable spawning substrate
Percentage of fine substrate	Substrate score

Physical - Temperature

Frost-free days	Minimum water temperature of 5 previous days
Mean annual air temperature	Water temperature rating
Mean annual water temperature	Maximum summer water temperature rating
Mean annual maximum water temperature	Maximum summer water temperature

Chemical

Conductivity	Minimum dissolved oxygen
Dissolved oxygen range	Nitrate nitrogen
Mean alkalinity	Calcium hardness rating
Mean annual 5-day biochemical oxygen demand	Magnesium hardness rating
Mean conductivity	Nitrate nitrogen rating
Mean platinum cobalt colour	Ph rating
Mean total hardness	Phosphate rating
Mean total organic carbon	Sulfate rating
Mean total phosphorus	Turbidity rating
Mean turbidity	Total alkalinity rating
Sulfate	

Appendix C/ Frequency of Occurrence of Independent Variables that were found significant in 85 models, excluding tests of weighted usable area (WUA) (from Fausch *et al.* 1988)

Independent Variable	Frequency Used	*Models with ≥20 df
Drainage basin variables:		
Reach elevation	4	1
Drainage area	4	-
Mean basin elevation	3	1
Channel morphometry variables:		
Mean depth	11	5
Mean width	6	3
Surface area	6	2
Pool area	4	-
Width-to-depth ratio	4	1
Mean pool depth	3	-
Section gradient measured in field	3	-
Flow variables:		
Mean monthly flow	5	5
Mean summer flow	3	-
Habitat structure variable:		
Area of all cover	8	1
Length of undercut bank	4	-
Area of overhanging riparian vegetation	3	1
Area of rubble, boulder, and aquatic vegetation substrate	3	-
Biological variables:		
Number of fish species	6	6
Species range	5	5
Physical variables (substrate and temperature):		
Percent substrate embeddedness	5	-
Mean annual water temperature	4	4
Frost-free days	3	3
Mean annual air temperature	3	3

Appendix C/ Frequency of Occurrence of Independent Variables that were found significant in 85 models, excluding tests of weighted usable area (WUA) (from Fausch *et al.* 1988)

Independent Variable	Frequency Used	*Models with ≥20 df
Chemical variables:		
Dissolved oxygen range	7	7
pH rating	6	-
Mean alkalinity	4	4
Mean conductivity	4	4
Mean total phosphorus	4	4
Minimum dissolved oxygen	4	4
Mean annual 5-day biochemical oxygen demand	3	3
Mean platinum-cobalt colour	3	3
Mean total organic carbon	3	3
Mean turbidity	3	3

*Models with 20 or more degrees of freedom and coefficients of determination larger than 0.50